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Demonstration of Silicon Nanocrystalline Lasers and Amplifiers

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Disclaimer

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Demonstration of Silicon Nanocrystalline Lasers and Amplifiers
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Abstract

A Si laser, fabricated using the conventional technologies, would constitute the missing link that has hindered a completely Si-based photonic system. This report summarizes a feasibility study effort to fully characterize a silicon nanocrystal based optical waveguide laser/amplifier.

Introduction/Background

The creation of a laser would have profound consequences. A silicon laser made using the conventional silicon-manufacturing technologies would be a disruptive new technology. It bridges the crucial missing link that has made a completely silicon-based photonic system elusive. The fact that this laser can be both extremely small (dimensions of only a few 10's of microns) and silicon based (CMOS compatible) enables arrays of such lasers to be integrated with standard IC chip technology. Being able to fabricate arrays of lasers on an IC chip enables a host of promising optical technologies and devices (e.g. optical interconnects, optical computing, and a variety of new types of optically based biological and chemical sensors).

This feasibility study and a previous related project began as a result of a "Nature" article by an Italian research group (Pavesi et al.) [1] which reported optical gain as high as 100 cm^{-1} for Silicon nanocrystals imbedded in silicon dioxide substrates. We have fabricated a series of Si nanocrystal waveguide structures. Oakridge National Laboratory's ion implantation facility was used to develop a silicon ion implantation process and recipe that produced embedded silicon nancrystals having an intense and broadband photoluminescence centered a ~750nm wavelength when optically pumped by a UV source. The higher index region containing the silicon nancrystals showed good waveguide confinement. However, the silicon nanocrystals showed no optical gain when we pumped with 413nm CW light from a Krypton ion laser. Recently, optical researchers from the University of Rochester, in collaboration with the Pavesi group, showed that there are two decay mechanisms associated silicon nanocrystal photoluminescence, a fast component and a slow component. The fast component has a decay time constant of a few nanoseconds, while the slow component has a decay time constant of 10s of microseconds. They showed that the fast component is the one associated with optical gain while the slow component displays no gain. Based on this new research finding, we proposed to fully re-characterize our samples using a high powered pulsed UV laser.

Research Activities

We proposed to conduct a complete set of laser gain measurements of our Si nanocrystal samples using tripled Nd:YAG pump laser emitting at 355nm, which delivers pulses powerful enough to saturate the samples and has a pulse width comparable with the luminescence decay time. We had fabricated Si nanocrystal waveguide samples that exhibited luminescence at room temperature and whose waveguiding properties we also propose to fully characterize here.

Most experiments seeking to demonstrate optical gain have been done using the Variable Stripe Length (VSL) technique, in which a ribbon-shaped portion of the sample is optically pumped. The strength and spectrum of the amplified spontaneous emission (ASE) (or perhaps just the spontaneous emission if there is no gain!) are monitored as the length of the excited “ribbon” is varied. A longer gain region gives more gain, more and more light. This technique is attractive because a probe source is not needed; spontaneous emission self-seeds the gain region. On the other hand, calibration and deconvolution of the results are extremely difficult. As the stripe length changes, so does the solid angle subtended by the detector, the degree of optical saturation, the optical spectrum, and other parameters. A book chapter [2] and scholarly article [3] have explored the various pitfalls of the VSL technique, which we conclude produces at best “circumstantial evidence” for optical gain in semiconductor-doped waveguide samples. It remains to do the “gold standard” experiment: put in a light beam and have it exit the sample brighter than it entered. This is what we aim to do.

Results / Technical Outcome

We set up a pulsed, frequency-tripled Nd:YAG laser to produce powerful 355 nm pulses of ~5 nsec duration. We used a beam homogenizer to provide a 1 mm “ribbon” of 355nm pump light with less-severe hot spots, raising the average pump fluence applied to our damage-prone samples. Our pump-delivery optics allowed the pump spot to be translated and we recorded “variable strip length” and shifting excitation spot” data. We first demonstrated that the detection system is working by looking at a known laser material such as Ti:sapphire (Figure 1). The emission spectrum from the Si nanocrystal is centered around 725nm, as expected.

Along with the emission spectrum, we need to measure the luminescence lifetime in order to assess the optical gain. (Larger oscillator strengths give bigger cross sections and shorter emission lifetimes.) Since radiation-less decay acts in parallel with fluorescence, the observed lifetime is actually a lower bound. Based on the data of Figure 2, (certainly not single-exponential,) we infer a lifetime ~30 nsec for the fast peak. To put this in perspective, note that for the 589 nm sodium D line, with near-unit oscillator strength, the lifetime is ~16 nsec. So, assuming the observed decay is dominated by radiation, this is a strong transition. The emission spectrum, when calibrated, yields a large peak gain cross section near 4 x 10^{-17} cm^2.

Since our samples are in the form of waveguides, we need to get some information about the guiding characteristics—how many modes are guided, what is the numerical aperture, how bad is the loss. For this purpose, we set up a Metricon prism coupler, a machine designed to measure refractive indices and thicknesses of layers on substrates. Sample spectra are shown in Figure 3. Since we had on hand a 633 nm He-Ne laser and an 800 nm laser diode, we were able to probe at two different wavelengths. Sharp dips in the reflectivity-vs-index spectra correspond to guided modes. The main points of the spectra are (1) guided modes exist, and (2) for each wavelength and polarization, there is only one mode. This is probably optimum for doing unambiguous pump-probe experiments because there will not be any confusion about mode overlap factors etc. The thickness derived from these measurements is near 0.5 μm, as expected from the ion-implantation conditions. Note that whereas the substrate has a refractive index near 1.46 (as evidenced by the "knee" in the reflectivity,) the guided modes occur at effective indices from 1.53 to 1.56. This is a hallmark of a substantial (~0.1 – 0.15) refractive index difference between the doped and undoped material, and produces strong confinement of the guided wave. If this were a round-core fiber, we would say it had a large "numerical aperture." We noted that at 633 nm, a wavelength visible to the naked eye, the waveguide layer exhibited little scatter. This also bodes well for laser and/or amplifier work.

Once we have waveguide structures whose properties we understood, we recorded "variable stripe length" and "shifting excitation spot" data, which unfortunately did not show clear evidence of gain (Figure 4 & 5). However, by looking in detail at the emission spectra and luminescence transients as a function of pump fluence, we saw spectral shifts and changes in the time-evolution. These are interpreted as evidence of pump-induced bleaching (or some other energy-transfer process) in the samples. In a low-power 355-nm pump / 670-nm probe experiment, our inconclusive results suggest that higher pump fluence is needed.

Summary

This feasibility did not verify the lasing gain in Si nanocrystal material as reported by the Pavesi group and others. This can be attributed to a number of factors, including but not limited to sample preparation. The tantalizing results of Pavesi et al. [1] although continues to be controversial, are not the last word. There continues to be active research by various groups around the world on silicon-based light emitting nanomaterials and photonics structures [4-7]. In additional to ion implantation techniques, samples have been produced using alternative techniques—RF sputtering and plasma-enhanced chemical-vapor deposition, for example. Formation of "superlattices" (multiple layers of nanocrystal-doped silica sandwiched with undoped silica) has also been tried. There is clearly still plenty of room for discovery.

References

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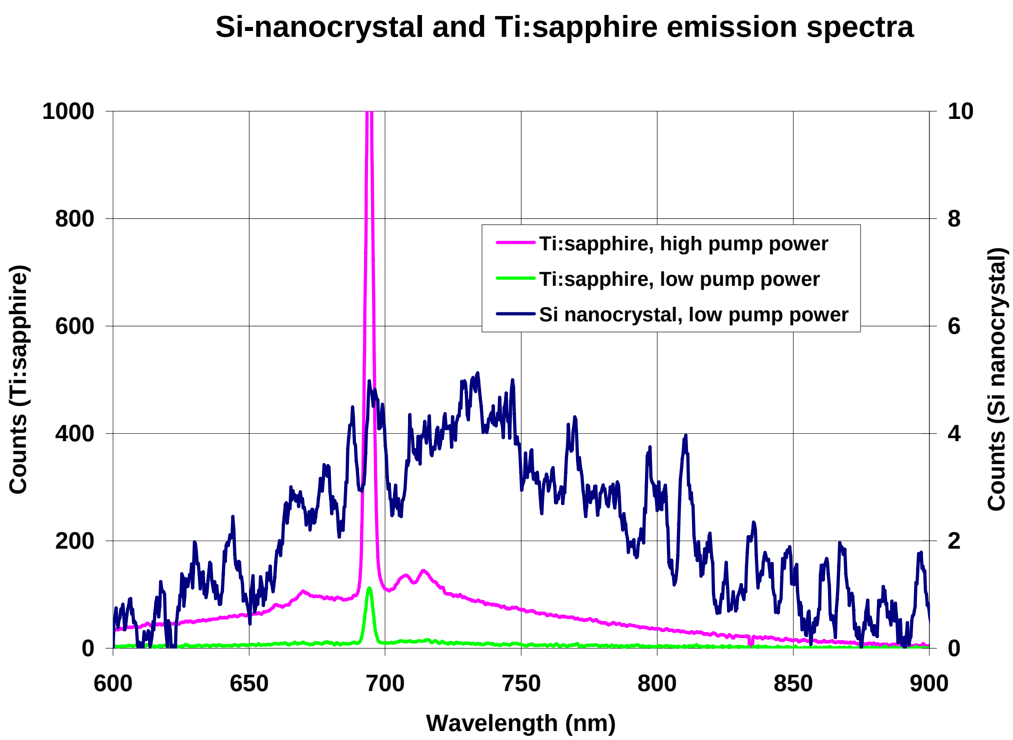

Figure 1 Si nanocrystal and Ti:sapphire emission spectra

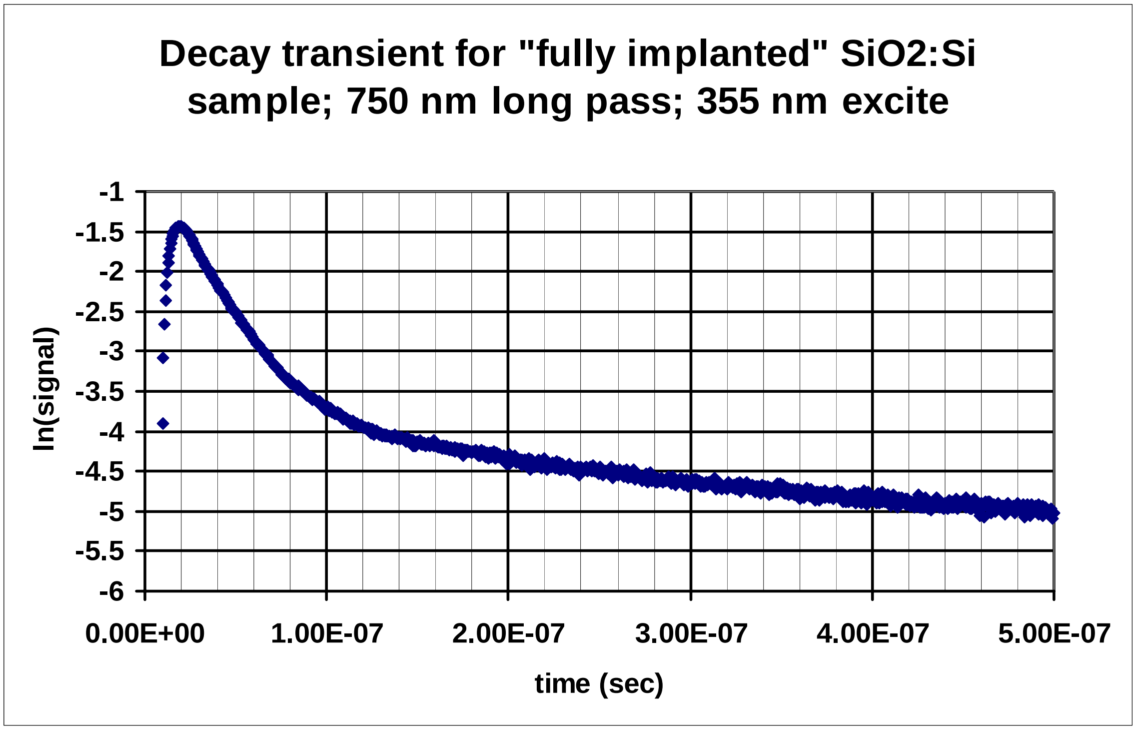

Figure 2 Fast ~30 nsec decay lifetime could imply a large oscillator strength

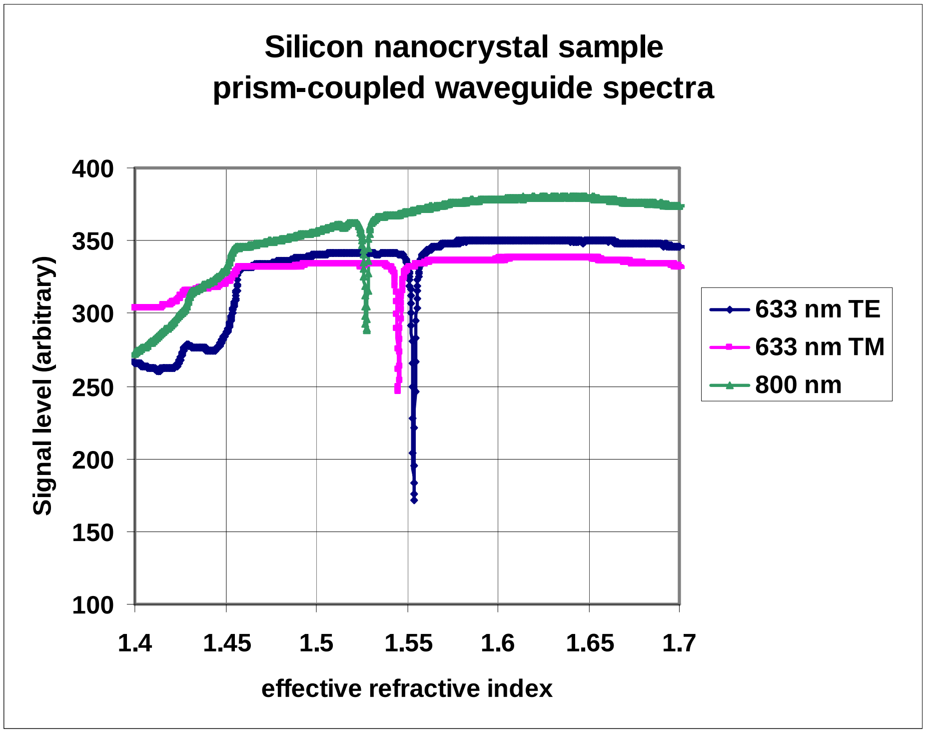

Figure 3 Waveguide mode spectra for 633 nm (two polarizations) and 800 nm

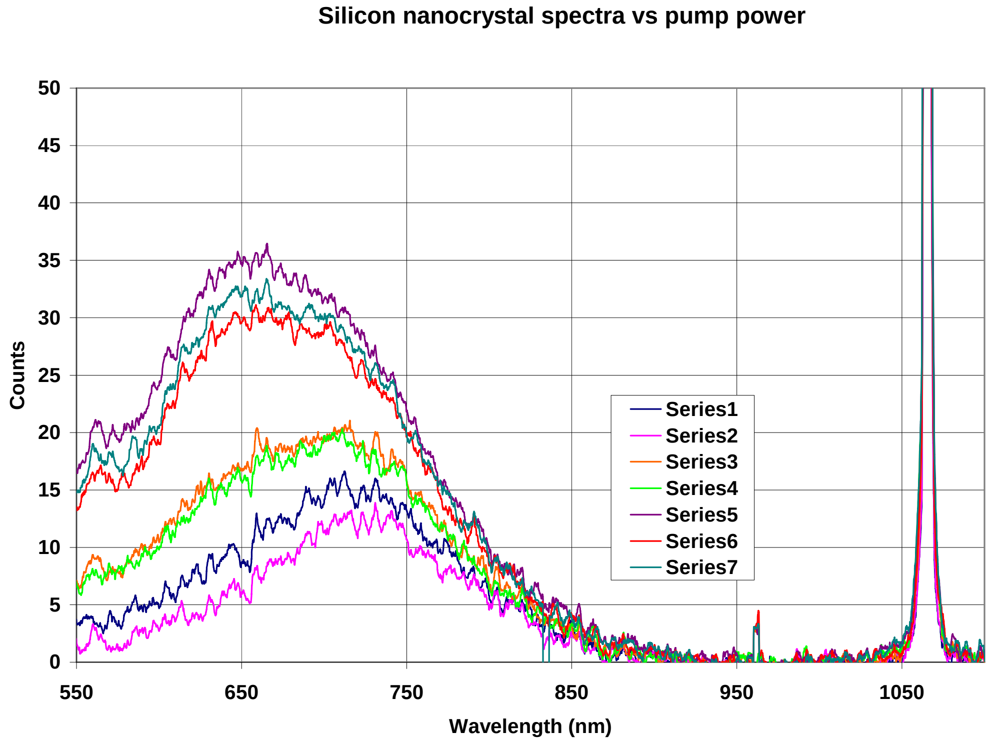

Figure 4 Emisison spectra as a function of pump power for the Si nanocrystal waveguide material show no clear evidence of gain. Spectrum suggest evidence of bleaching at shorter wavelength. The narrow spetra centered at 1063nm are leaked fundamental wavelength from the Nd:YAG laser.

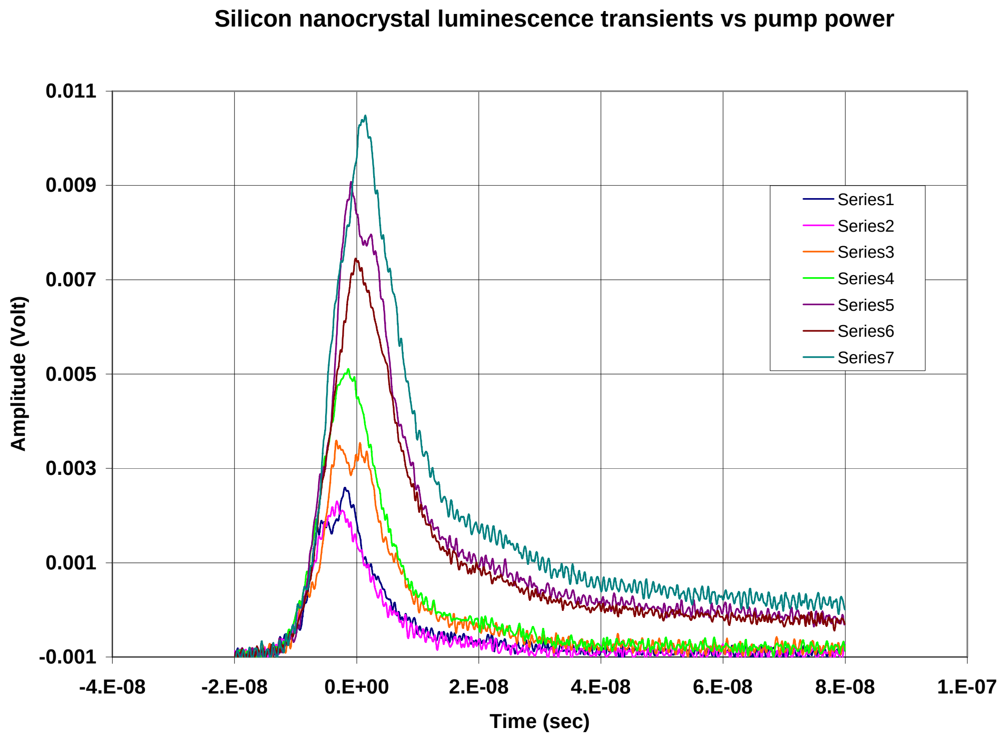

Figure 5 Silicon nanocrystal luminescence trasients as a function of pump power.